A New Technique to Measure Double-differential Charged-particle Emission Cross Sections Using Pencil-beam DT Neutrons

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For precise measurement of Double-differential Charged-particle Emission Cross Section(DDXc), a unique technique was developed. Utilizing an anticoincidence spectrum successfully extended lower limit of measurable energy for α-particle. The validity of the present technique was confirmed from the result that the obtained total cross section agreed with the evaluated value of ^{27}Al(n,xα) reactions. The measurements for beryllium were carried out. The results suggested more detailed analysis for ^{9}Be(n, charged particle) reactions was required.

1. Introduction

For fusion reactor development, nuclear data for the interaction of 14-MeV neutrons with reactor materials are of importance. Double-differential charged-particle emission cross section (DDXc) is needed to calculate nuclear heating and fundamental value for evaluation of material damage, i.e., PKA spectra, GPA and DPA cross sections. In particular use of several light nuclei such as beryllium, carbon and lithium in large quantities is planned in the blanket region of a fusion reactor. Charged-particle emission reactions of these materials are complex due to contributions from sequential decays and multi-body breakup. From this reason, theoretical calculations of energy spectra of emitted particles are difficult. This fact makes precise measurements of DDXc quite important.

The measurement of DDXc is difficult since charged-particle emission reaction has small cross section and generally background condition is high. Until now only a few data have been accumulated. In 1960s~80s, several early studies of charge-particle emission reactions induced by DT neutrons were carried out to investigate details of direct nuclear reaction, although spectra of emitted charged-particle in the whole energy range were not obtained [1,2,3]. In the author's group, E-TOF method was developed at OKTAVIAN in Osaka University [4] and measurements of DDXc for several medium heavy materials for fusion reactor were successfully carried out [5]. However, the method was a little hard to apply for precise measurement of lighter materials. The defects of these previous methods are in the following;

1. Signal-to-noise (S/N) ratio is bad due to a large number of background signals.
2. Low net count rate decreases statistical accuracy, or needs long time measurement.

3. Energy resolution of the detector is not so good.
4. The lower limit of detecting energy is relatively high.

Therefore development of a new technique aiming at improvement of these points is strongly required in order to realize accurate measurement in the whole energy range and with acceptable high-energy resolution.

In this study, we have developed a new measurement technique of DDXc using the pencil-beam DT neutron source and E-ΔE counter telescope. In the following sections, measurements of DDXc for aluminum and beryllium are described. Aluminum was chosen as a standard sample in order to confirm the validity of the present method. Since beryllium is regarded as one of the most important materials for the fusion reactor, the detailed measurements were carried out.

2. Experimental procedure

We used a pencil-beam DT neutron source of Fusion Neutronics Source (FNS) in Japan Atomic Energy Research Institute (JAERI). An accelerated deuterium beam bombers a tritium target and 14-MeV neutrons are generated. A large shielding structure consisting of Fe, Pb, Cd, and polyethylene is embedded into a concrete wall with a thickness of 2m to collimate the neutrons. There is a hole of 2cm in diameter pierced through the shielding structure and a 2cm-ϕ neutron beam is extracted. Characteristics of the beam, such as intensity, profile and neutron background, are well investigated [6]. Neutron flux at the outside of the beam is about 1×10^{4}~10^{6} times lower than at the inside of the beam. Using the neutron beam, we can arrange a detector very close to a sample material without any shield and therefore high S/N ratio and high-count rate can be achieved.

In the present study, a sample and detectors were located in an experimental vacuum chamber of 40cm-ϕ by 30cm in height. The chamber was set at the outlet of neutron beam. The distance from the neutron source to the sample was 380cm. A metal aluminum disc of 50μm thick and a metal beryllium disc of 20μm in thickness and 3cm in diameter were used as experimental samples. Figure 1 shows the experimental arrangement.

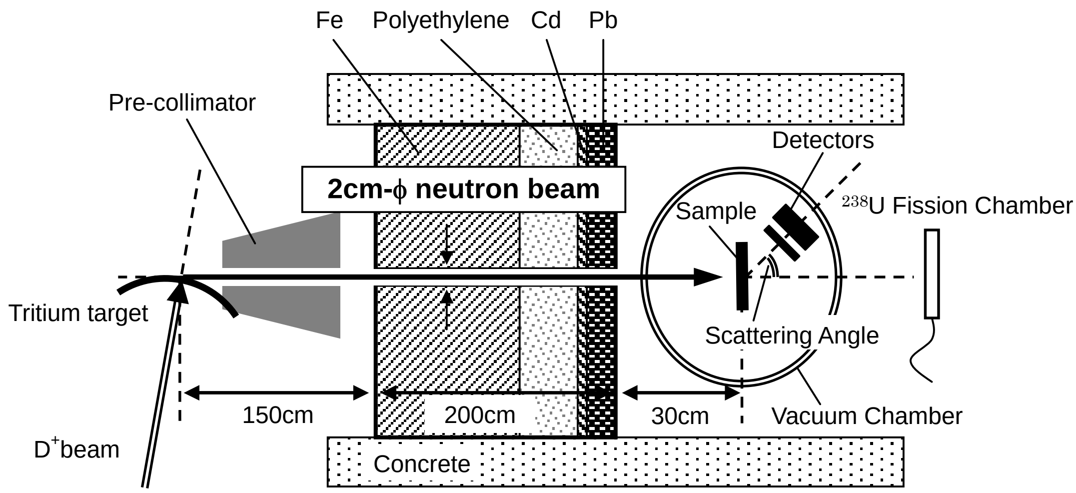

Fig. 1 Experimental arrangement

To distinguish kinds of charged particles, we used a counter-telescope system with two silicon surface barrier detectors of ΔE and E, and a two-dimensional MCA. The thicknesses of the ΔE and E detectors were 9.6μm and 700μm, respectively. The energy resolution of the telescope was about 100KeV (fwhm) for 5.486MeV α-particle from ^{241}Am α-source. Figure 2 shows a typical two-dimensional spectrum obtained in the measurement. In the coincidence measurement for α-particles, the lower limit of detecting energy was around 2.5 MeV. In order to extend the limit of measuring energy, we utilized an anticoincidence spectrum of ΔE detector as the spectrum below the lower limit energy of coincidence measurement. The reasons why we were able to use the anticoincidence spectrum were as follows;

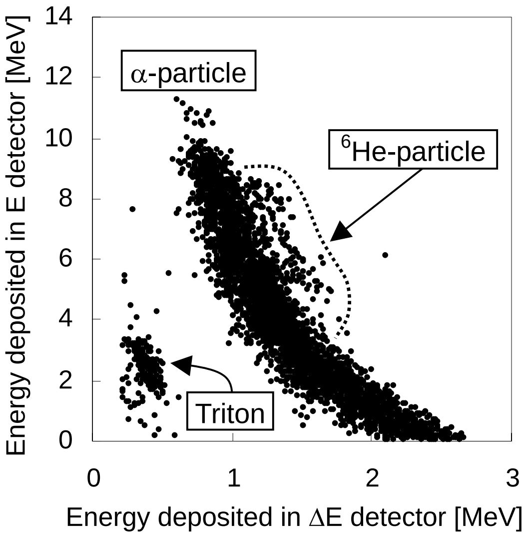

Fig.2 2D-spectrum obtained for the measurement of ^9Be(n, charged particle) reactions at 15 deg. in emitted angle

1. The thickness of ΔE detector was extremely thin and therefore the deposited energy of proton in the detector was up to about 600 keV.
2. The intensity of background signals in case of sample-out measurement were exceptionally low, which was only 10~15 counts per hour.

As a result, 600 keV ~ 1 MeV for the lower limit energy of α-particle measurement was achieved since only α-particle can be detected as the anticoincidence spectrum of ΔE detector over this energy. However if the sample emits heavier particles than α-particle from other nuclear reactions, it should be confirmed whether these particles are negligible. In the measurement for ^9Be, since ^9Be particles emitted from elastic scattering were actually measured, the effect had to be corrected.

3. Data analysis

In order to obtain the actual energy spectrum of emitted charged-particle, the measured spectrum must be corrected for energy loss in a sample. The relationship between real spectrum and measured spectrum is expressed in the following matrix equation;

$$\mathbf{M} = \mathbf{R} \cdot \mathbf{A} \qquad (1)$$

where, **A** is the actual spectrum, **M** is the measured spectrum, **R** is the response function that represents effects of the energy loss in a sample and the angular resolution according to the detector geometry. The matrix **R** was obtained by Monte Carlo calculation with SRIM-2003 [7] and our own post-processing codes. Then spectrum unfolding was carried out with our original code based on *the spectrum type Bayes estimation method* to obtain the real energy spectrum [8,9].

DDX $\sigma(E_n \to E, \theta)$ [barn/sr/MeV] is obtained by the following equation;

$$\sigma(E_n \to E, \theta) = \frac{R(E,\theta)}{k_{\Delta E} \cdot k_E \cdot \phi_n \cdot N \cdot dE \cdot d\Omega_{\Delta E} / 4\pi} \qquad (2)$$

where, $R(E,\theta)$ is the count rate for charged particles detected in energy bin E at scattering angle θ, $k_{\Delta E}$ and k_E are the efficiency of the detectors (for charged-particle, $k \cong 1$), ϕ_n is neutron flux, N is the number of target nuclei, dE is the energy bin width and $d\Omega$ is the solid angle of the telescope, respectively. The angular differential cross section (ADX) was obtained by integrating DDX over energy. The total cross section (TOX) was obtained by fitting ADX with Legendre polynomials and integrating it over angle.

In the present study, neutron flux was monitored with ^{238}U Fission Chamber relatively and absolute value was determined by the foil activation method with Al. For the standard cross section, 122.2mb for ^{27}Al(n,α) reaction in JENDL-3.3 was used.

4. Results and discussion

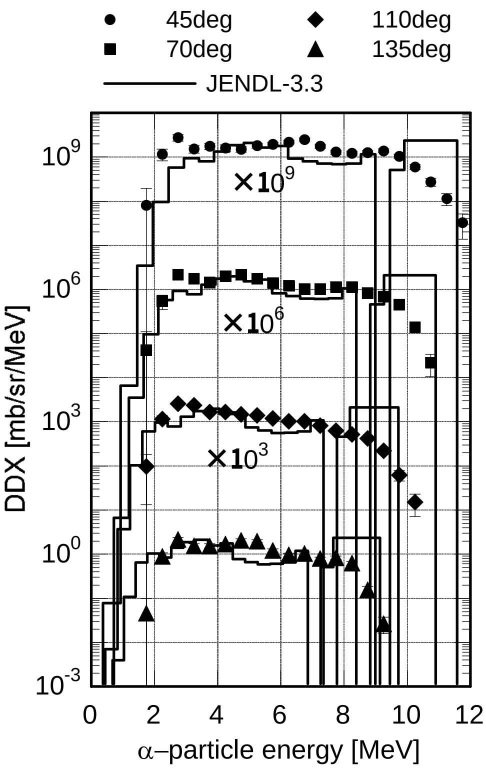

Fig.3 DDX measured for ^{27}Al(n,xα) reactions at each scattering angles in LAB-system

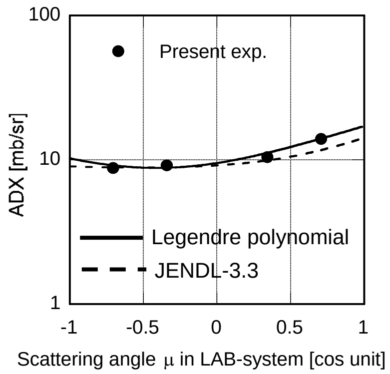

Fig.4 ADX measured for ^{27}Al(n,xα) reactions at each scattering angles in LAB-system

Data obtained in the measurements were compared with the values evaluated for 14.2MeV neutron incidence. Error bars indicated in Figs. 3-7 include statistical error only.

Figure 3 shows DDXs obtained for ^{27}Al(n,xα) reactions at scattering angles of 45, 70, 110 and 135 deg. There were slight differences in the details of structure between obtained DDX and the evaluation in JENDL-3.3. Figure 4 shows ADX for ^{27}Al(n,xα) reactions. Agreement of the measured ADX with JENDL-3.3 is fairly good. Obtained TOX was 134 ± 2 mb, which was also in good agreement with JENDL-3.3 of 126.2 mb. From this result, the validity of the present experimental and analytical techniques was confirmed.

Figure 5 shows the measured DDX for ^{9}Be(n,xα) reactions. DDX above 0.8MeV of emitted α-particle energy was obtained. The structures in the obtained DDX at backward scattering angle and in lower energy region were different from DDX reproduced from JENDL-3.3. Figure 6 shows obtained ADX. ADX evaluated in JENDL-3.3 agreed well with obtained ADX in forward scattering angles although underestimated at backward scattering angles. This disagreement would be resulting from wrongness of the branching ratio assumed in evaluation of JENDL-3.3 for each process from which α-particle is emitted. The analysis of the obtained DDX aiming at the investigation of the branching ratio is in progress.

Figure 7 shows ADX for $^{9}Be(n,t)$ reaction. Measured ADX includes contributions from both $(n,t_0)^{7}Li_{(GS)}$ and $(n,t_1)^{7}Li^{*}_{(EX=0.48MeV)}$ reactions. Although isotropic angular distributions were assumed in JENDL-3.3 for these reactions, obtained ADX showed gentle forward peaked distribution. This result suggests that the contribution of the direct nuclear reaction process is dominant. The preliminary result of TOX obtained was 17.9 ± 0.6 mb, which was slight smaller than JENDL-3.3 of 18.9 mb. This disagreement should be caused by the uncertainty of ADX at backward scattering angle, which couldn't be obtained from the present experiment. The analysis with DWBA calculation would be desirable in order to obtain more precise information.

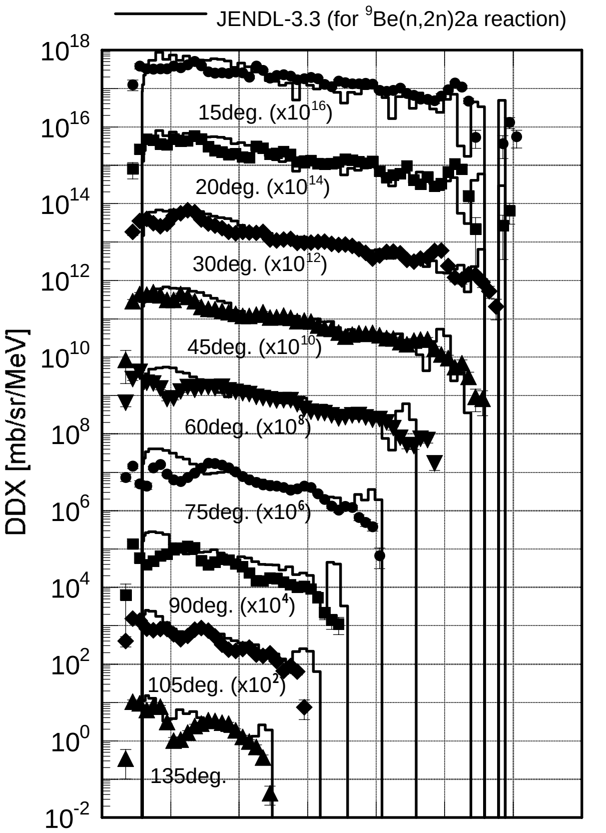

Fig.5 DDX measured for $^{9}Be(n,x\alpha)$ reactions at each scattering angles in LAB-system

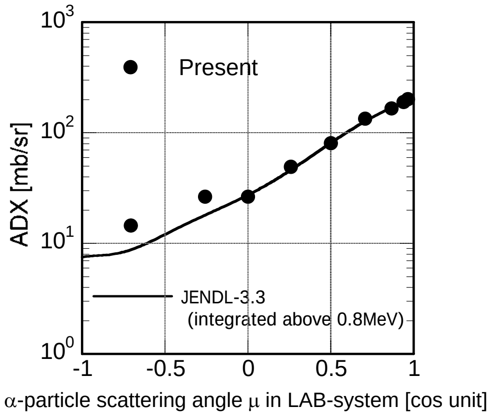

Fig.6 ADX measured for $^{9}Be(n,x\alpha)$ reactions at each scattering angles in LAB-system

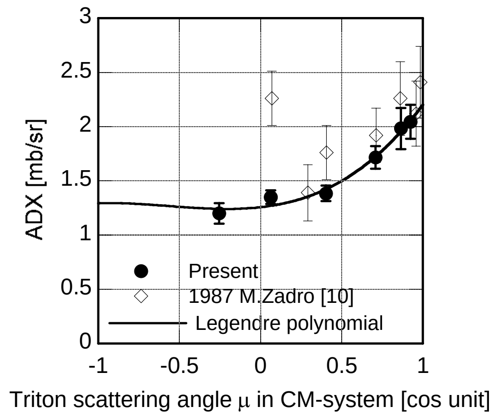

Fig.7 ADX measured for $^{9}Be(n,t)$ reactions at each scattering angles in CM-system

5. Conclusion

A unique technique for precise measurement of DDXc was developed. The present technique realized good S/N ratio, relatively high-count rate and good energy resolution. Since utilizing an anticoincidence spectrum extended lower limit of measurable energy for α-particle, 600KeV~1MeV for the lower limit was available. The present technique was valid from the result of measurement for the ^{27}Al(n,xα) reactions. Detailed measurements for beryllium were carried out. Slight differences appeared between measured data and evaluation or previous experimental values. These results suggest more precise analysis for each process included in ^{9}Be(n,xa) reactions is required.

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